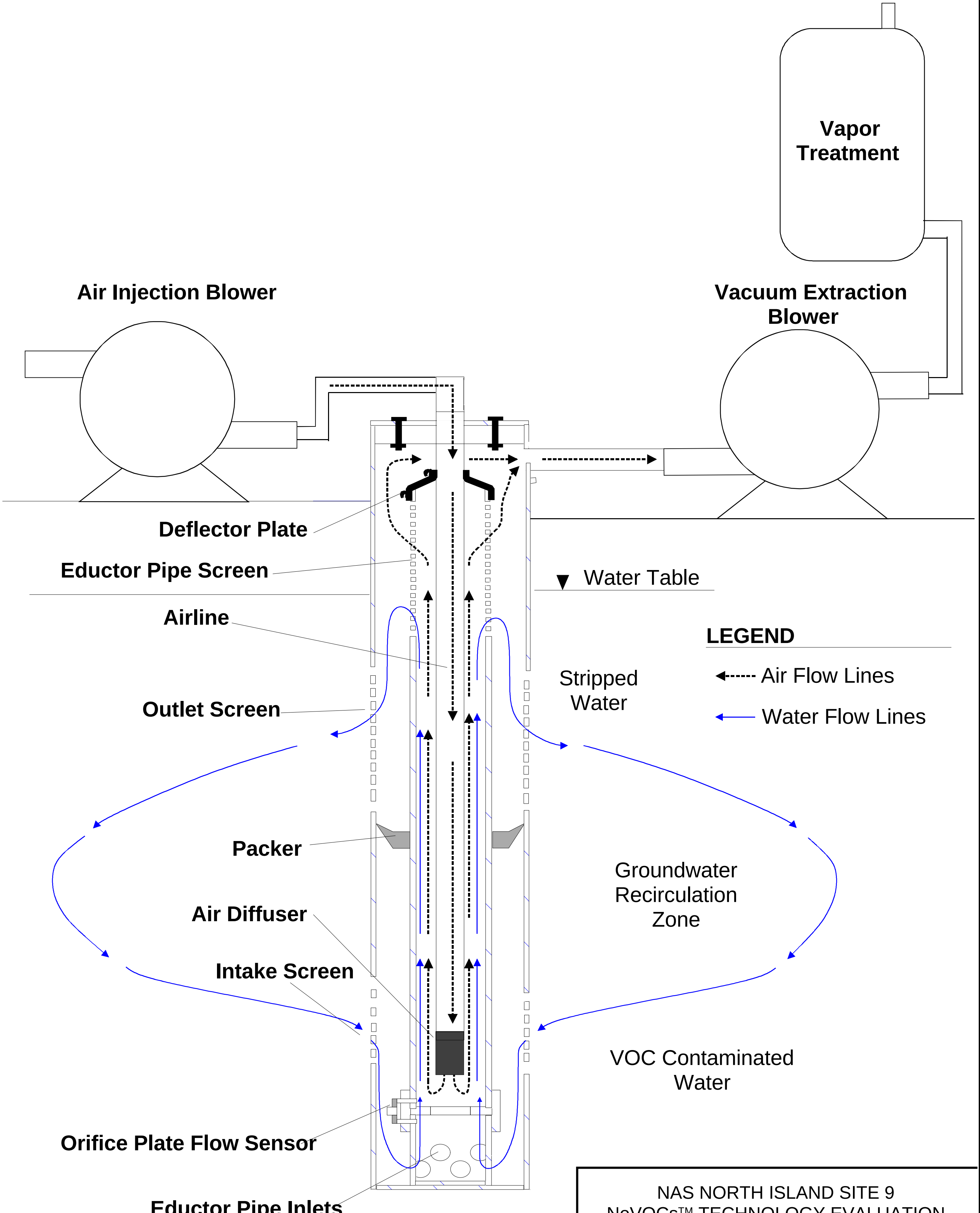


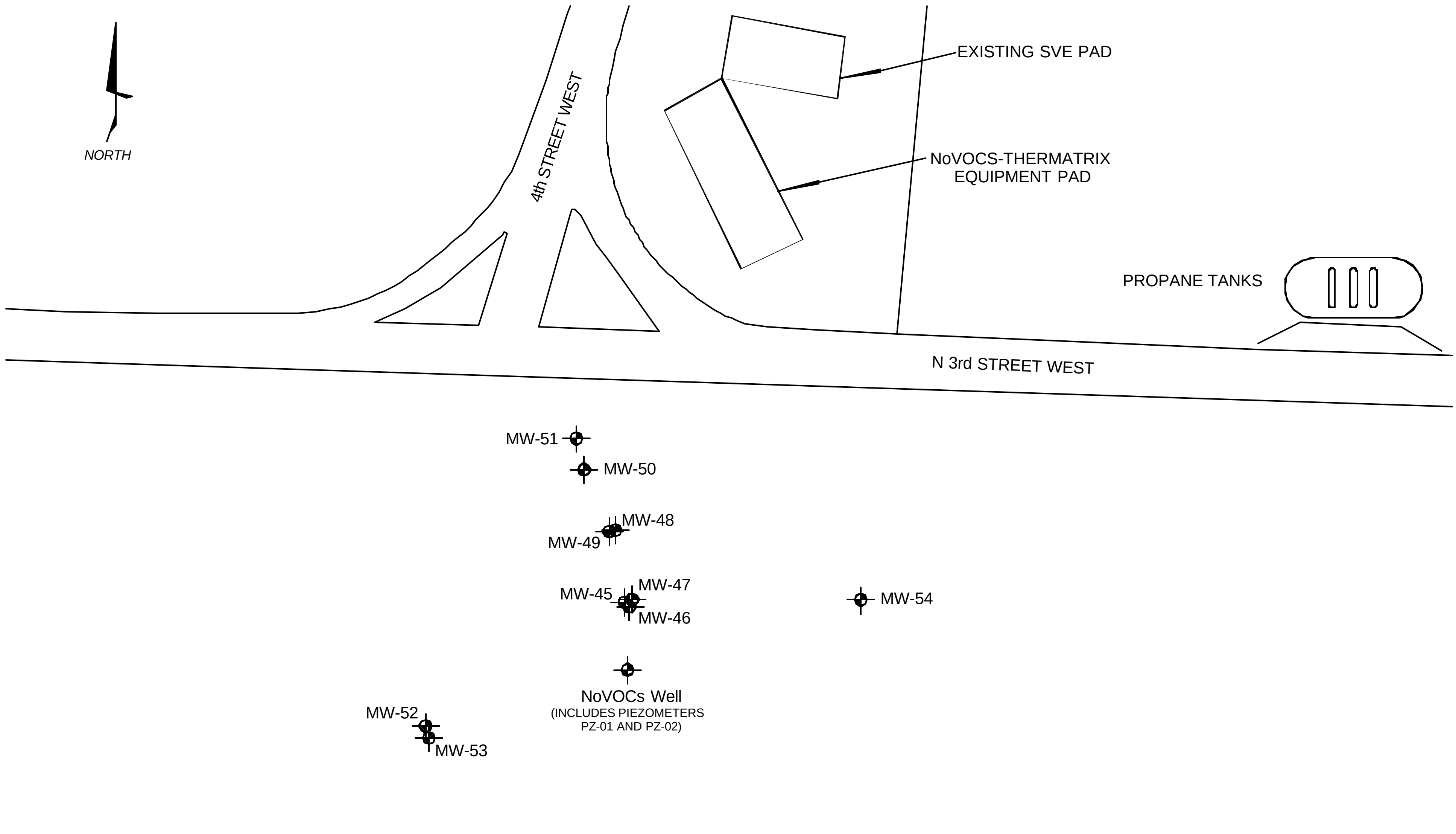
Not to scale

MODIFIED FROM MACTEC 1998

NAS NORTH ISLAND SITE 9
NoVOCs™ TECHNOLOGY EVALUATION

FIGURE 2-1
NoVOCs™ SYSTEM

Tetra Tech EM Inc.



LEGEND

APPROXIMATE LOCATION OF MONITORING WELL OR NoVOCs WELL

0 50 100

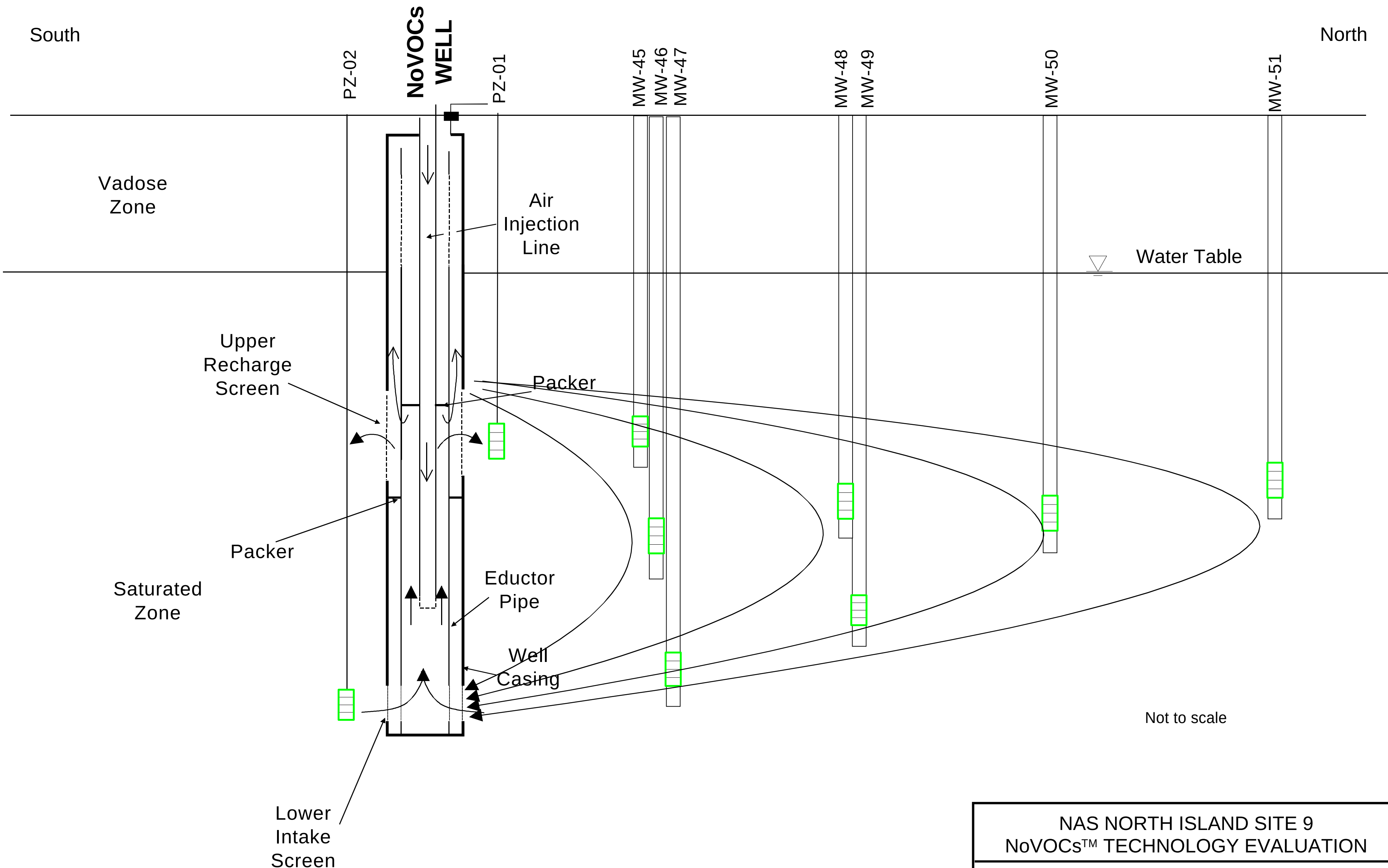
SCALE IN FEET

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 2-2

WELL LOCATIONS

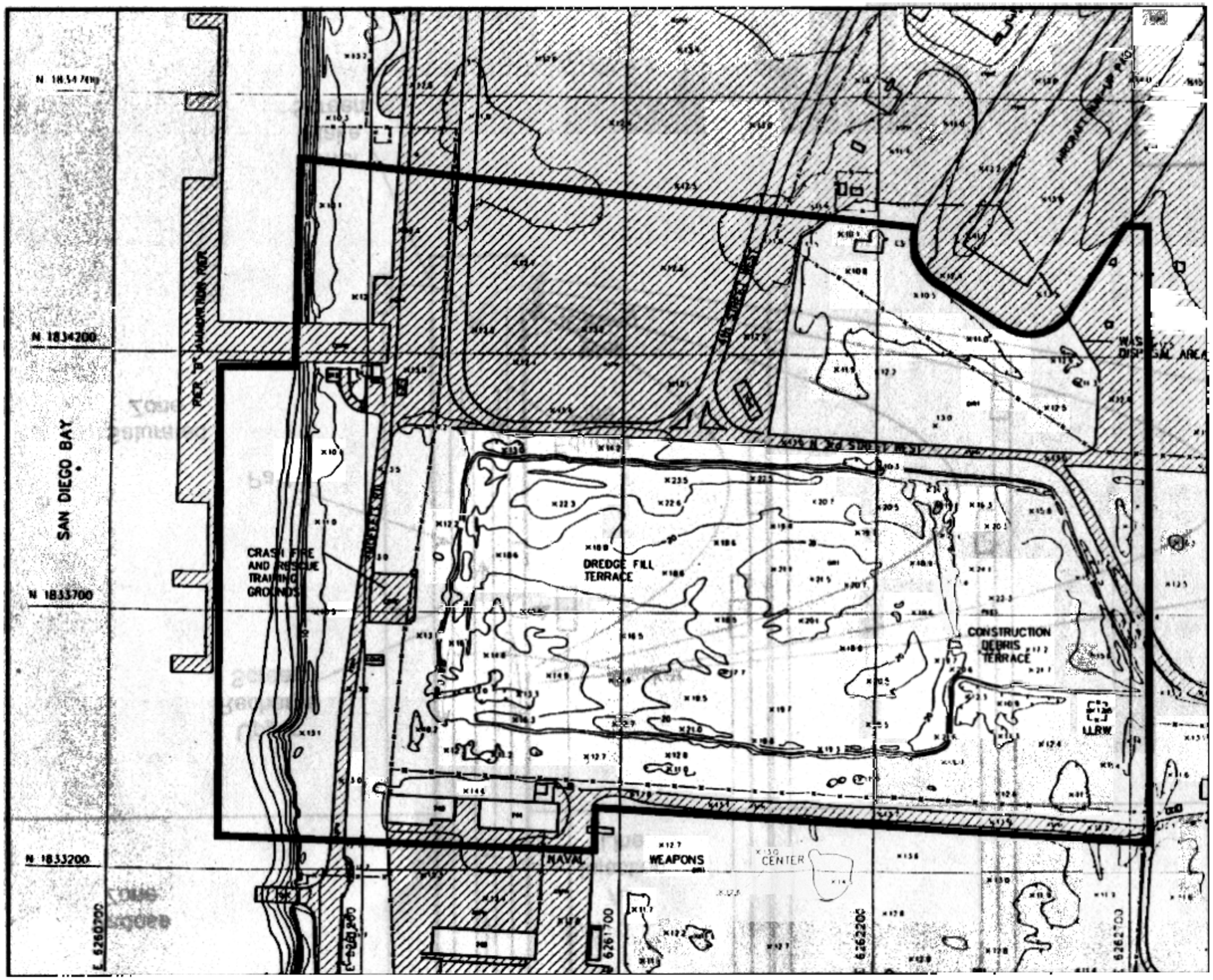
Tetra Tech EM Inc.



NAS NORTH ISLAND SITE 9
NoVOCs™ TECHNOLOGY EVALUATION

FIGURE 2-3
GENERALIZED CROSS-SECTION

Tetra Tech EM Inc.



NORTH

LEGEND

20	CONTOUR LINE
	FENCE
	ROAD AND STREET
	BUILDING
X 12.3	SPOT ELEVATION
	PAVEMENT (CONCRETE OR ASPHALT)
LLRW	LOW-LEVEL RADIOACTIVE WASTE STORAGE AREA
	SITE 9 BOUNDARY

NOTES:

1. BASE MAP ADAPTED FROM PHOTGRAMMETRY BY BECHTEL NATIONAL, INC., 1994.
2. ELEVATION DATUM IS MEAN LOWER LOW WATER.
3. COORIDINATES ARE IN THE CALIFORNIA COORDINATE SYSTEM (1983) ZONE 6 BASED ON THE NORTH AMERICAN DATUM (1983).

0 250 500

SCALE IN FEET

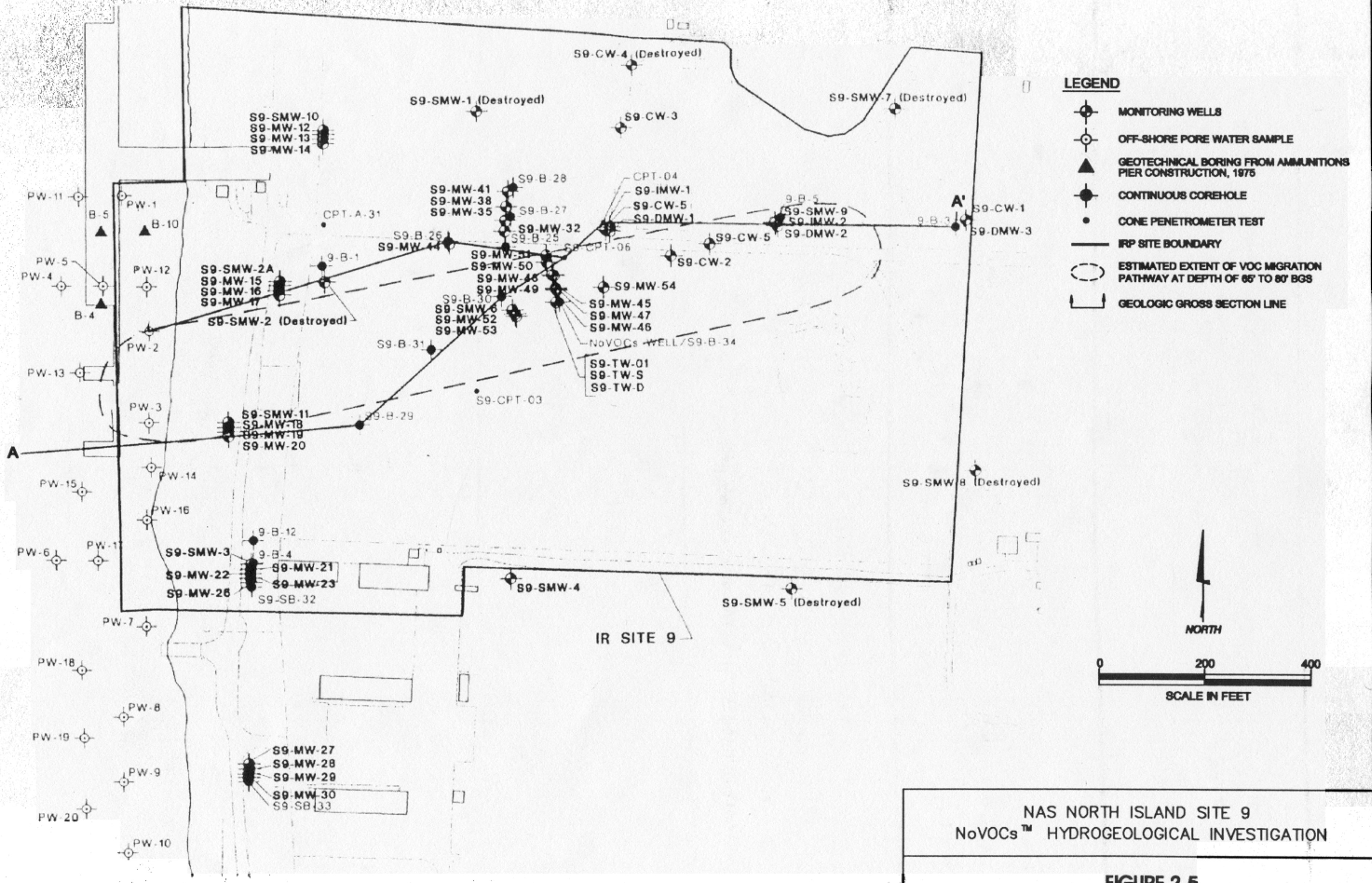
NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 2-4

SITE 9 TOPOGRAPHIC ELEVATIONS

Tetra Tech EM Inc.

SOURCE: MODIFIED FROM JACOBS 1994



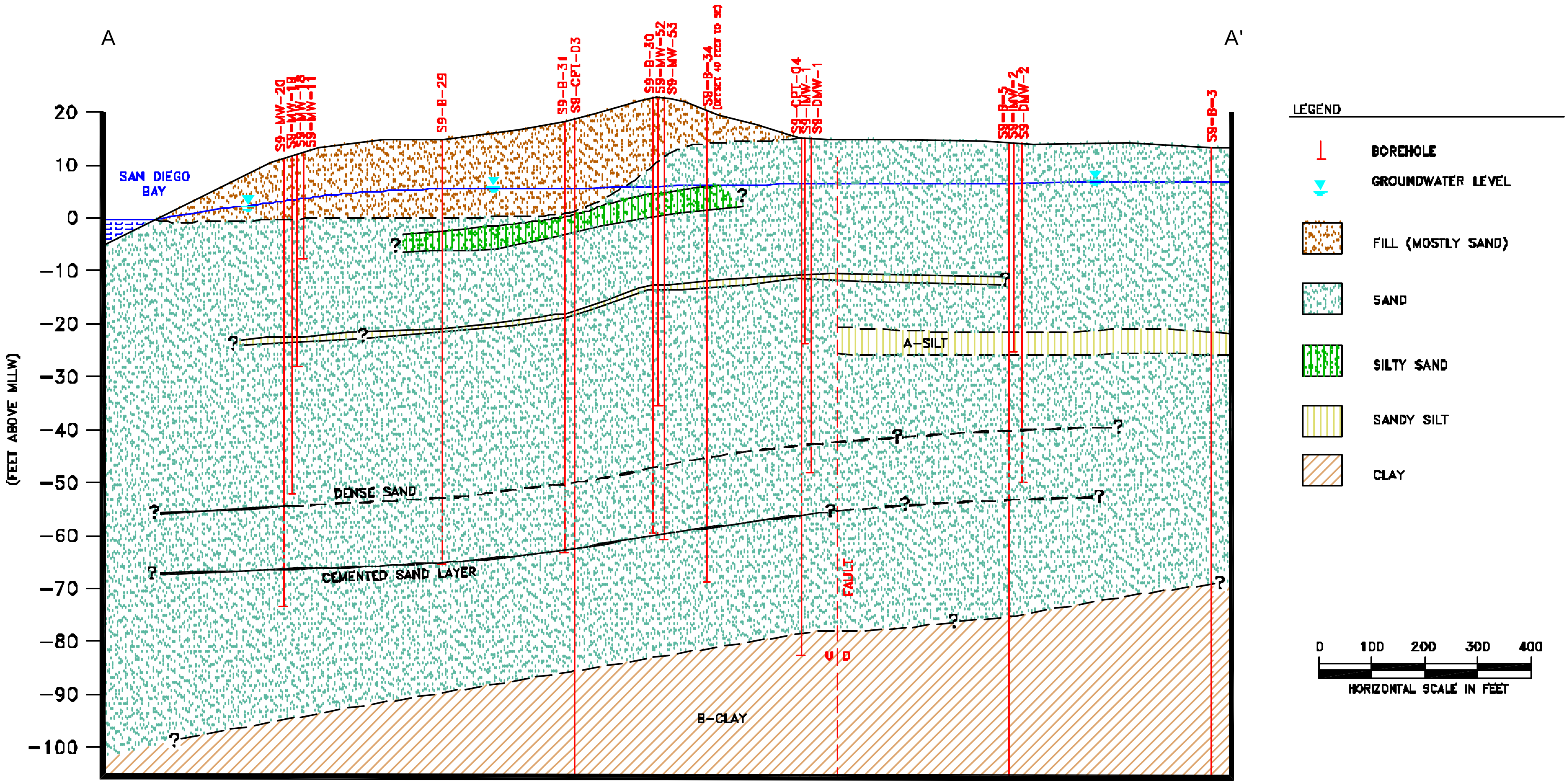
NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 2-5

GEOLOGIC CROSS-SECTION LOCATION

Tetra Tech EM Inc.

SOURCE: MODIFIED FROM BECHTEL (1998)



NAS NORTH ISLAND SITE 9
NaVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 2-6

GEOLOGIC CROSS SECTION A-A'

Tetra Tech EM Inc.

SOURCE: MODIFIED FROM BECHTEL 1998.

TABLE 2-1

WELL SCREEN INTERVALS
NoVOCs HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Well	Description	Distance From NoVOCs Well (feet)	Screen Interval	
			Depth (feet bgs)	Elevation (feet relative to MLLW)
IW-01	NoVOCs well	0	43 to 47 and 72 to 78	-21.3 to -25.3 and -50.3 to -56.3
MW-45	Cross-gradient monitoring well	29.8	42 to 47	-20.0 to -25.0
MW-46	Cross-gradient monitoring well	27.7	57 to 62	-35.4 to -40.4
MW-47	Cross-gradient monitoring well	31.1	72 to 78	-49.9 to -55.9
MW-48	Cross-gradient monitoring well	61.9	52 to 57	-28.6 to -33.6
MW-49	Cross-gradient monitoring well	61.7	67 to 72	-43.6 to -48.6
MW-50	Cross-gradient monitoring well	90.7	52 to 57	-36.9 to -41.9
MW-51	Cross-gradient monitoring well	104.6	49 to 54	-35.1 to -40.1
MW-52	Downgradient monitoring well	93.0	41 to 46	-19.1 to -24.1
MW-53	Downgradient monitoring well	93.1	72 to 77	-50.4 to -55.4
MW-54	Upgradient monitoring well	107.9	38 to 78	-18.0 to -58.0

Notes:

bgs Below ground surface

MLLW Mean lower low water level

3.0 TIDAL INFLUENCE STUDY

This section describes the configuration for and procedures of the tidal influence study and presents its results. The NoVOCs™ system began operation during the tidal influence study. The effects of NoVOCs™ system operation on groundwater levels is also discussed.

3.1 CONFIGURATION AND PROCEDURES

Tetra Tech conducted a tidal influence study from April 20 through 30, 1998 to measure natural fluctuations in water level at the site caused by tidal influences. Water level changes in the aquifer caused by NoVOCs™ system operation were also recorded because the system was started and shut down multiple times during the study period. Tetra Tech installed pressure transducers in nine observation wells in the immediate vicinity of the NoVOCs™ system and measured changes in water levels in the observation wells before system startup and during system operation. Measurements were collected before startup of the NoVOCs™ system to measure natural fluctuations in water levels at the site caused by tidal influences and to establish baseline groundwater elevation conditions. Water levels were measured during system startup and operation to assess the magnitude and extent of the water level changes caused by the NoVOCs™ system. This information was used to assist in evaluating the extent of the NoVOCs™ treatment cell.

To document water level changes in the aquifer caused by the NoVOCs™ system, Aquistar pressure transducers were installed in observation wells MW-45 though MW-53 (Figure 2-2). Transducers were not installed in piezometers PZ-01 and PZ-02 because the inner diameters of the piezometers were smaller than the outer diameter of the transducers. The installation of a transducer in observation well MW-54 was precluded by the presence of a multilevel diffusion sampler inside the well.

The pressure transducers had a ¾-inch outer diameter and were rated at 15 pounds per square inch (psi). All of the transducers are automatically compensated with barometric pressure changes (i.e., the pressure transducer readings are automatically adjusted to current atmosphere pressure). The transducers were installed approximately 6 feet below the water surface, and water level elevations were measured manually using an electronic water level sounder in each observation well immediately before the transducers were installed. Each transducer was connected to either a single- or multi-channel data logger. Before the transducers were installed, the data loggers were programmed to collect pressure readings every 10 minutes. The pressure readings are converted to feet of water above the transducer and then to water level elevation. The transducers were used to collect groundwater elevation data from the observation wells from April 20 to 30, 1998. The transducers were removed from the observation wells on April 30, 1998. Water level readings were obtained with an electronic sounder before the transducers were removed to provide an additional accuracy check.

3.2 RESULTS

This section presents the results of the tidal influence study that was conducted to evaluate natural fluctuations in water levels at the site caused by tidal influences. The changes in water levels recorded in each of the observation wells were plotted versus time. These plots are presented in Appendix B. Figures B1 through B4 depict the fluctuations in water levels in the observation wells over the 10-day duration of the study. Figures B5 through B8 present the water levels in the observation wells for 12 hours of the first day of NoVOCs™system operation. Figure B9 shows the water level fluctuation in San Diego Bay during the tidal study. The tidal influence and NoVOCs™system influence are discussed separately in the following sections.

3.2.1 Tidal Influence

This section summarizes the effects of tidal influence on the groundwater levels. A detailed discussion of the analysis of the tidal influence study data is provided in Section 5.1.

Based on Figures B1 through B4, the water level readings follow a cyclical pattern in all observation wells included in the tidal study. Figures B1 through B4 illustrate the increase and decrease in groundwater levels caused by tidal fluctuations in San Diego Bay. Maximum groundwater level fluctuations measured in the observation wells ranged from 0.56 to 0.73 feet, depending on the location of the observation well. The amplitudes of the tidal fluctuations in water levels were highest for observation wells closest to San Diego Bay (MW-52 and MW-53). The other observation wells monitored during the tidal influence study (MW-45 through MW-51) are all located at approximately the same distance from San Diego Bay; the amplitudes of the tidal fluctuations in these wells are similar to one another.

The cyclical pattern of groundwater level fluctuation can be seen for all observation wells and correlates with published tide charts for San Diego Bay with a time lag ranging from approximately 46 to 96 minutes, depending on observation well location and magnitude of the tidal fluctuation. The time lag also depends on the degree of hydraulic communication between the bay and the wells. The range of time lags is similar for each of the observation wells because of the similar distance relative to San Diego Bay. The aquifer zone is generally in good hydraulic communication with the San Diego Bay.

3.2.2 NoVOCs™System Influence

Figures B5 through B8 show groundwater elevations during approximately 12 hours of the first day of the study that included several NoVOCs™system startups and shutdowns. Table 3-1 lists the start and stop times for the NoVOCs™system on April 20, 21, and 22, 1998, as reported by the Navy. Groundwater level changes caused by startup and shutdown of the NoVOCs™system on April 20, 1998, are evident in the water level data for well cluster MW-45, MW-46, and MW-47, located approximately 30 feet from the NoVOCs™well (Figure B5). The water level data for observation wells MW-45 (the upper screened well in this cluster) and MW-46 (intermediate screened well) show water level increases after system startup. The groundwater elevation increase in well MW-45 was approximately 0.15 foot of water. Observation well MW-46, the intermediate depth well, shows a water level increase of approximately 0.05 foot of water. Observation well MW-47, the deep screened well, shows a water level decrease of approximately 0.025 foot. This pattern of water level increases and decreases associated with the operation of the NoVOCs™system is expected based on the monitoring well screen locations relative to the NoVOCs™well screen locations. The deep screened well experiences a drop in water level as water is drawn toward the NoVOCs™well intake, and the upper screened wells experience increases in water level as water is lifted inside the NoVOCs™well, and discharges into the upper aquifer. In well pair MW-48 and MW-49 (located approximately 62 feet from the NoVOCs™well) and in wells MW-50 and MW-51 (located approximately 91 and 105 feet, respectively, from the NoVOCs™well), water level changes associated with NoVOCs™system operation are not apparent (Figures B6, B7, and B8).

TABLE 3-1

START AND STOP TIMES FOR THE NoVOCs SYSTEM
NoVOCs HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Date	Time[a]	Action
April 20, 1998	10:01	Start
	10:01	Stop
	10:04	Start
	10:05	Stop
	10:18	Start
	10:24	Stop
	15:54	Start
	16:20	Stop
	18:08	Start
	18:32	Stop
	18:50	Start
	18:51	Stop
	18:56	Start
	19:00	Stop
	19:10	Start
April 21, 1998	16:20	Stop
	16:23	Start
	16:40	Stop
	18:45	Start
April 22, 1998	12:30	Stop
	13:03	Start
	13:12	Stop
	13:40	Start
	14:01 through 14:19	Six stop and start cycles to check auto shutdown functions
	14:19	Start (system in continuous operation)

Note:

a Rounded to nearest minute

4.0 AQUIFER TESTING

A series of aquifer tests were conducted at the demonstration site from July 27 through August 5, 1998, to obtain information on hydraulic communication between various portions of the aquifer beneath the site, as well as data for estimating values of aquifer hydraulic parameters such as hydraulic conductivity, transmissivity, storativity, and anisotropy. In addition, the aquifer tests were conducted to obtain data for calculating well efficiencies for the two screened intervals of the NoVOCs™ well.

Aquifer testing was conducted using the NoVOCs™ well (IW-01) as the pumping or injection well. Two piezometers and 10 observation wells were available for water level measurements. An inflatable packer was used to isolate the two screened intervals within the NoVOCs™ well to allow pumping from each screened interval separately. The aquifer tests, in the order conducted, were as follows:

- Step drawdown test in the upper screened interval conducted on July 27, 1998
- A 32-hour constant discharge pumping test in the upper screened interval conducted on July 28 and 29, 1998
- Injection test in the upper screened interval conducted on July 31, 1998
- Step drawdown test in the lower screened interval conducted on August 1, 1998
- Dipole flow test with pumping in the lower screened interval and injection in the upper screened interval conducted on August 5, 1998

A constant discharge pumping test for the lower screened interval was not conducted because of the excessive volume of water that would be generated and the prohibitive cost of water disposal.

4.1 PRETESTING ACTIVITIES

Before initiating the aquifer tests, certain downwell components of the NoVOCs™ system were removed, the well screens and filter pack were redeveloped, and aquifer testing equipment was installed. A description of each pretesting activity is provided in the following subsections.

4.1.1 NoVOCs™ Equipment Removal

To allow access for aquifer testing equipment, downwell components of the NoVOCs™ system were removed, except for the 8-inch diameter outer casing and the prepacked screen on the eductor casing at 72 to 78 feet bgs (-50.4 to -58.0 feet MLLW). In addition, piezometers, PZ-01 and PZ-02, set in the filter pack adjacent to the intake and recharge screens of the NoVOCs™ well, were not removed and were used as monitoring points during the aquifer tests. The downhole components removed included the 5-inch, schedule 40 polyvinyl chloride (PVC) eductor casing, the 2-inch PVC airline and diffuser, all packers, and downhole probes and meters.

4.1.2 Video Survey and Well Screen Development

To assess the condition of the NoVOCs™ well screens, a downhole video camera was lowered into the well to visually inspect the condition of the well casing and well screens. Two downwell video surveys of the NoVOCs™ well were conducted: one after internal NoVOCs™ well components were removed, and the other after well redevelopment and cleaning of the well screens. The camera was lowered on a taped cable so that the depth of the camera was known. The camera was capable of rotating up to 360 degrees on command. During the initial video survey, heavy orange iron staining on the well casing and well screens was observed. In addition, excessive orange iron flocculant was observed in the water column along with orange iron bioslime in the well screen intervals. Orange iron precipitant was also observed on the eductor pipe, eductor screen, and air line during removal of the internal well components. These observations suggest that iron precipitation and microbiological growth in the well are occurring. Both of these factors may impair the performance of the NoVOCs™ system by obstructing the well screen and filter pack material. Groundwater samples collected from the well by MACTEC confirmed that microorganisms were present in the NoVOCs™ well at high levels (Personal Communication from Scott Donovan, Bechtel 1998).

To remove the microbiological growth and precipitant, the well was redeveloped using surge and pump methods and hydrochloric acid was added to the well water. Approximately 2.5 gallons of hydrochloric acid were tremmied into the upper and lower screen intervals of the NoVOCs™ well, and the well water was agitated for a period 30 minutes. After cleaning the NoVOCs™ well screens with acid, the video camera was lowered into the well a second time to evaluate the effectiveness of well cleaning and development.

The second video survey showed that redevelopment and cleaning were effective in removing precipitant and microbiological growth in the well screens. In addition, the orange iron flocculant was removed from the water column within the well. Review of the integrity of the well casing during the second survey indicated that the well was intact with no signs of damage. However, a manufacturing defect in the upper well screen was observed. The screen slots in the upper well screen are unevenly cut, and about 30 percent of the slots do not completely penetrate the PVC casing. This defect limits the efficiency of the upper screen interval and may reduce the available water level rise in the NoVOCs™ well during recharge into the aquifer through the upper screen interval.

4.1.3 Aquifer Test Equipment Installation and Configuration

The first set of aquifer tests were conducted in the upper screened interval of the NoVOCs™ well and consisted of step drawdown, constant discharge, and injection tests. The second set of aquifer tests were conducted in the lower screened interval of the NoVOCs™ well and consisted of step drawdown and dipole flow tests. This section describes installation and configuration of aquifer testing equipment.

Pump and Packer

Pumping equipment configuration was identical for the step drawdown test and constant discharge pumping test conducted in the upper screened interval (Figures 4-1 and 4-2). To pump only the upper screened interval of the NoVOCs™ well, the two screened intervals were hydraulically separated using a 5-inch-diameter by 5-foot-long inflatable Baski packer. The inflatable packer was set between the two screened intervals at a depth of approximately 62 to 67 feet bgs (-40.3 to -45.3 feet MLLW). The pump used for the aquifer tests was a 4-inch stainless steel Grundfos submersible pump with a capacity of 100 gallons per minute. The pump was installed above the packer with its intake at approximately 55 feet bgs (-33.3 feet MLLW). The pump and the packer system were set in the NoVOCs™ well using a 2-inch diameter steel drop pipe (Figure 4-1). The drop pipe was secured at the well head and connected to a 2-inch diameter PVC discharge line. After the pump was set, the packer was inflated to a pressure of 70 pounds per square inch using a pressurized nitrogen cylinder. The packer's pressure was monitored throughout the pumping tests at the well head using a pressure gauge. The same equipment was used for the stepdrawdown and dipole flow tests conducted in the lower screened interval of the NoVOCs™ well (Figures 4-4 and 4-5). The packer was installed at approximately 56 to 61 feet bgs (-34.3 to -39.3 feet MLLW) and the submersible pump was set immediately below the packer at approximately 65 feet bgs (-43.3 feet MLLW).

Pressure Transducers and Data Loggers

Pressure transducers manufactured by AquiStar were installed in observation wells MW-45 through MW-54 and in the pumping well (one transducer above the packer system and one transducer below the packer). The pressure transducers used were pressure rated between 5 and 30 psi. The higher pressure rating transducers were installed in wells anticipated to exhibit the greatest change in water level (observation wells MW-45 through MW-49 and the pumping well). Transducers with pressure ratings of 5 psi were installed in observation wells farthest from the NoVOCs™ well (MW-50 through MW-54) because smaller changes in water levels were expected during the pumping tests.

The transducers were connected to single- and multi-channel data loggers. The pressure readings by the transducers were automatically adjusted to the atmosphere pressure so that no barometric pressure correction is needed for the pressure/water level readings by the transducers. In addtion, barometric efficiency was expected to be low for the testing aquifer under unconfined condition. Therefore, barometric efficiency was not calculated and barometric pressure correction for observed water levels was not conducted.

During transducer installation, the depth to groundwater was measured with an electronic water level sounder before lowering the transducer into the well. The pressure transducer was then connected to the data logger and the transducer was lowered into the well. The transducer was set at a depth so that it would remain submerged during the pumping test at a depth below water not exceeding the pressure rating of the transducer. The pressure transducer cable was secured to the well head and the surface using duct tape, so that no movement occurred during the pumping test. After the transducer was secured, a reading of the length of the column of water above the transducer was recorded.

During the aquifer tests, the data loggers for the NoVOC™ well and observation wells MW-45, MW-46, and MW-47 were constantly connected to a laptop computer to view recorded data. Data loggers for observation wells MW-48 through MW-54 were periodically connected to a laptop to confirm that water level readings were being recorded properly. In addition, transducer data were periodically checked by collecting water level measurements using an electronic water level sounder.

Other Equipment

During the aquifer tests, the pumping and injection rates were regulated using a variable rate controller, a flow control valve, and two inline flow meters. The flow meters used were a McCrometer electronic flow meter with totalizer and a Precision flow meter with totalizer. The meters were installed on the discharge pipe at the well head. The flow meters were calibrated in the field by measuring the time required to fill a 5-gallon bucket with water pumped through the discharge line.

All water generated during the pumping tests was piped to on-site storage tanks to await chemical characterization and subsequent disposal. To accommodate the volume of water generated during the pumping tests, four 20,000-gallon tanks were staged on site for storage of the extracted groundwater. Water quality parameters including pH, oxidation and reduction potential, specific conductance, temperature, and dissolved oxygen were measured during development and removal of the well water. Horiba U10 and YSI 2000 water quality meters were used to measure the water quality parameters in the field. The instruments were calibrated daily in accordance with the manufacturer's instructions.

4.1.4 Data Logger Programming

The data loggers were programmed using the length of the column of water above the transducer, depth of water below the top of well casing, and the survey elevation on the top of the casing so that subsequent readings were relative to MLLW. The data loggers were programmed for each pumping test to collect data at specific times and frequencies. Because of significant water level responses to changes in pumping rate (including starting and stopping pumping), the data loggers for the NoVOCs™ well and observation wells MW-45 through MW-47 were programmed to collect data at a higher frequency immediately following any change in pumping rate. The programmed data collection schedule was as follows: every half-second for 20 readings, every second for 50 readings, every 2 seconds for 60 readings, every 5 seconds for 60 readings, every 10 seconds for 30 readings, every minute for 20 readings, every 2 minutes for 20 readings, every 5 minutes for 12 readings, every 10 minutes for 18 readings, and every 20 minutes for 500 readings. (This schedule was reinitiated following any change in pumping rate and was generally terminated before the last step reached completion.) Collecting water level measurements in this manner provided data at higher frequencies when the rate of water level change was greater. Data loggers for observation wells MW-48 through MW-54 were programmed to collect data at lower frequencies, typically once per minute. All data were downloaded from the data logger to a computer and the data logger was reset between each aquifer test.

4.2 STEP DRAWDOWN TEST OF THE UPPER SCREENED INTERVAL

Tetra Tech conducted a step drawdown test in the upper screened interval of the NoVOCs™ well to estimate the optimal pumping rate for a constant discharge pumping test, and to estimate the well efficiency and specific capacity of the upper screened interval of the NoVOCs™ well. Test procedures and results are discussed below.

4.2.1 Procedures

On July 22, 1998, Tetra Tech conducted an initial step drawdown test on the upper screened interval of the NoVOCs™ well to estimate the optimal pumping rate for a constant discharge pumping test and the well efficiency and specific capacity of the upper screened interval of NoVOCs™ well. The step drawdown test was conducted by separating the upper and lower screened sections of the NoVOCs™ well using a packer system and pumping the upper screened interval of the well with a submersible pump (Figure 4-1), as described in Section 4.1.3. Based on observations of water levels in the recharge and intake piezometers (PZ-01 and PZ-02), the integrity of the inflatable packer seal between the upper and lower screens was determined to have been compromised during the initial test.

A second step drawdown test in the upper screened interval of the NoVOCs™ well was conducted on July 27, 1998. During the second test, water was first pumped at a rate of 43 gpm for about 17 minutes to check the integrity of the packer system. The water level in piezometers PZ-01 and PZ-02 remained stable during pumping of the upper screened interval, indicating that the packer seal was effective. Water was then pumped at 10 gpm for 11 minutes, 15 gpm for 45 minutes, and 20 gpm for 45 minutes. Water levels in the NoVOCs™ well and the surrounding observation wells were monitored using pressure transducers to measure changes in water level within the aquifer. A summary of the step drawdown test for the upper screen interval of the NoVOCs™ well is provided in Table 4-1.

4.2.2 Results

The pressure transducer and hand measurement data from the NoVOCs™ well (upper and lower intervals) and observation wells MW-45 through MW-54 are presented in Appendix C as Figures C1 through C7. Results for observation well MW-49 are not available because of a data logger malfunction.

Decreases in water levels were recorded in the pumping well (Figure C1) and observation wells MW-45 through MW-54 (Figures C2 through C7). The water level changes in the pumping well and observation wells exhibited similar patterns in response to changes in pumping rate; however, the responses decreased with distance from the NoVOCs™ well and with depth of the observation wells. When pumping at 20 gpm, the pumping well exhibited a maximum water level decrease of about 14 feet; observation well MW-45 (approximately 30 feet from the pumping well) showed a water level decrease of 0.6 foot; and observation well MW-51 (about 105 feet from the pumping well), showed a water level decrease of about 0.03 foot. The observation wells exhibited an almost immediate response to changes in pumping rate, suggesting that the aquifer has good communication in both the horizontal and vertical directions.

4.3 CONSTANT DISCHARGE PUMPING TEST OF THE UPPER SCREENED INTERVAL

A constant discharge pumping test in the upper screened interval was conducted following the step drawdown test in the upper screened interval of the NoVOCs™ well and following complete water level recovery in the pumping well, the observation piezometer, and the observation wells. Constant discharge pumping test procedures and results are discussed below.

4.3.1 Procedures

Based on the results of the step drawdown test (Section 4.2.2), 20 gpm was selected as the pumping rate for the constant discharge pumping test in the upper screening interval of the NoVOCs™ well. On July 28 through 30, 1998, Tetra Tech conducted a constant discharge pumping test to estimate the hydraulic conductivity, transmissivity, storativity, and anisotropy of the shallow aquifer. The constant discharge pumping test was conducted by isolating the upper and lower screened intervals of the NoVOCs™ well using a packer system and pumping the upper screened interval of the well with a submersible pump (Figure 4-2), as described in Section 4.1.3. Water was pumped at a constant discharge of 20 gpm for about 32 hours. Afterward, recovery data from the pumping well and the observation wells were collected for 24 hours. Recovery rates were recorded in the pumping well and all observation piezometers and wells. Pumping equipment remained in the pumping well until recovery monitoring was complete. Water levels in the NoVOCs™ well and the surrounding observation wells were monitored using pressure transducers to measure changes in water level within the aquifer. A summary of the constant discharge pumping test for the upper screened interval of the NoVOCs™ well is provided in Table 4-2.

4.3.2 Results

The pressure transducer and hand measurement data from the NoVOCs™ well and observation wells MW-45 through MW-54 are presented in Appendix D as Figures D1 through D6. Results for observation well MW-50 are not available because of a data logger malfunction.

Drawdown in the pumping well was measured at about 16 feet. With the exception of the pumping well, changes in water levels in the observation wells are difficult to discern without tidal corrections to determine actual drawdown. Tidal corrections for the constant discharge pumping test data are discussed and applied in Section 5.1.

4.4 INJECTION TEST OF THE UPPER SCREENED INTERVAL

The pumping equipment used for the step drawdown and constant discharge pumping tests were left in the well for the injection test in the upper screened interval. Injection test procedures and results are discussed below.

4.4.1 Procedures

The injection test was conducted in the NoVOCs™ well by injecting a constant rate of potable water through the upper screened interval of the NoVOCs™ well. Clean tap water was brought to the site using a fire hose and was stored adjacent to the NoVOCs™ well in a 300-gallon holding tank. Water was initially introduced to the NoVOCs™ well by gravity flow from the holding tank to the NoVOCs™ well. Water flow rates were controlled by a flow valve and were measured using an inline flow meter and totalizer. Flow rate was monitored closely so that a constant flow rate was injected. On July 30, 1998, approximately 1.5 hours after starting the injection test, water injection was terminated because particulate material was observed in the tap water being injected into the NoVOCs™ well. The particulate material was identified as scaling from the hose used to transport the potable water. Approximately 1,200 gallons of water had been injected during the initial injection test. To remove the particulate material injected, approximately 6,000 gallons of water was pumped from the upper screened interval of the NoVOCs™ well. To eliminate the particulate problem, the water storage tank was eliminated and a new fire hose was plumbed directly to the NoVOCs™ well through a flow control value and inline flow meter (Figure 4-3). Before reinitiating water injection, the aquifer was allowed to stabilize overnight.

On July 31, 1998 through August 1, 1998, Tetra Tech conducted an injection test to obtain information on the recharge capacity and specific capacity of the upper screened interval of the NoVOCs™ well. Potable water was injected at rates of 5, 15, and 22 gpm for a period of about 1 hour at each rate. Potable water was also injected at a rate of 30 gpm for 4 minutes and 25 gpm for about 14 minutes. Based on the water injection rate and duration, a total of approximately 3,000 gallons of water was injected into the aquifer during the injection test. After water injection was stopped, water levels continued to be monitored for approximately 14 hours of recovery. A summary of the injection test for the upper screened interval of the NoVOCs™ well is provided in Table 4-3.

4.4.2 Results

The pressure transducer and hand measurement data from the NoVOCs™ well (upper and lower intervals), and observation wells MW-45 through MW-54 are presented in Appendix E as Figures E1 through E7. An increase in water level was recorded in the injection well and in observation wells MW-45 through MW-54. The water levels in the injection well and observation wells exhibited similar patterns in response to changes in pumping rate; however, the response decreased with distance from the NoVOCs™ well and with depth of the observation wells. The upper screened interval recharged clean tap water at a flow rate of 22 gpm for 1 hour with a 14.4 foot increase in water level. When the flow rate was increased to 30 gpm, the water level quickly increased another 3.6 feet to about 18 feet above the initial water level and began discharging at the ground surface. The injection rate was decreased to 25 gpm for about 15 minutes, during which groundwater elevations stabilized at about 17 feet above the initial water level. This information shows that the upper well screen can recharge clean tap water at an injection rate near the design pumping rate of the NoVOCs™ system (25 gpm). However, the injection rates were run for only 1 hour each and, therefore, the corresponding increase in water level may not represent complete stabilization of the aquifer.

4.5 STEP DRAWDOWN TEST OF THE LOWER SCREENED INTERVAL

After the injection test was completed and the aquifer had recovered, the pumping equipment was reconfigured for aquifer testing of the lower screened interval of the NoVOCs™ well (72 to 78 feet bgs). The procedures for and results of the step drawdown test of the lower screened interval are discussed below.

4.5.1 Procedures

On August 1 and 2, 1998, Tetra Tech conducted a step drawdown test to assess the well efficiency and specific capacity of the lower screened interval of the NoVOCs™ well. The step drawdown test was conducted by separating the upper and lower screened intervals of the NoVOCs™ well using a packer system and pumping the lower screened interval of the well with a submersible pump (Figure 4-4), as described in Section 4.1.3. Water was first pumped at a rate of 40 gpm for 10 minutes to check the integrity of the packer system. Water was then pumped at rates of 50, 64, and 30 gpm for a period of about 1 hour at each rate. After pumping stopped, water levels continued to be monitored for approximately 13 hours of recovery. A summary of the step drawdown test for the lower screened interval of the NoVOCs™ well is provided in Table 4-4.

4.5.2 Results

The pressure transducer and hand measurement data from the NoVOCs™ well (upper and lower intervals) and observation wells MW-45 through MW-54 are presented in Appendix F as Figures F1 through F7. Results for observation well MW-50 are not available because of data logger malfunction. A decrease in water level was recorded in the pumping well and observation wells MW45 through MW54. The water levels in the pumping well and observation wells exhibited similar patterns in responses to changes in pumping rate; however, the responses decreased with distance away from the NoVOCs™ well and with depth of the observation wells. A drawdown of greater than 20 feet was observed in the lower screened interval of the pumping well. The observation wells exhibited an almost immediate response to changes in pumping rate, suggesting that the aquifer has good communication in both the horizontal and vertical directions.

4.6 DIPOLE FLOW TEST

After the aquifer had recovered from the step drawdown test of the lower screened interval, the pumping discharge line was redirected to inject pumped water through the upper screened interval. The procedures for and results of the dipole flow test are discussed below.

4.6.1 Configuration and Procedures

On August 5 through 7, 1998, Tetra Tech conducted a dipole flow aquifer test (simultaneous pumping and injection of groundwater) to investigate groundwater circulation through the NoVOCs™ system and to calibrate the downhole inline flow meter. The dipole flow test was conducted by pumping a constant rate of groundwater from the lower screened section of the NoVOCs™ well and injecting groundwater into the upper screened section of the NoVOCs™ well (Figure 4-5). Groundwater was pumped and injected at rates of 5, 10, 15, 20, and 25 gpm for periods ranging from 54 to 71 minutes for each rate. Pumping and injection flow rates were measured using an inline flow meter. Flow measurement was also attempted using an orifice plate (the same orifice plate used in the NoVOCs™ well); however, the magnahelic used to measure pressure across the orifice plate was damaged during the test and reliable measurements could not be collected. Instead, pumping and injection flow rates were measured using an inline flow meter. A total of approximately 4,600 gallons of water were pumped and injected during the dipole flow test. A summary of the dipole flow test for the upper and lower screened sections of the NoVOCs™ well is provided in Table 4-5.

4.6.2 Results

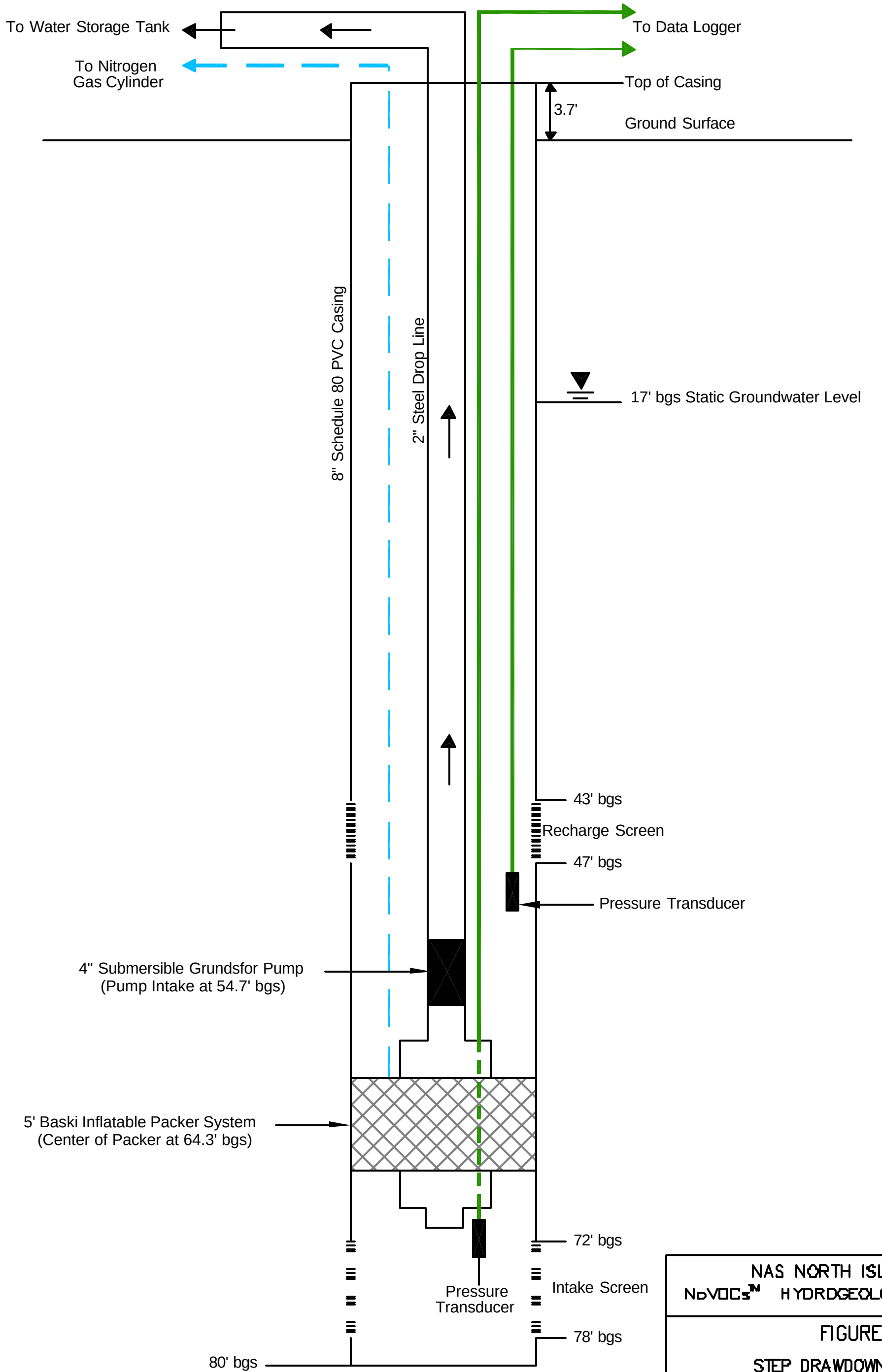
Dipole flow test data are presented in Appendix G. Figure G-1(Appendix G) shows pressure transducer data for the pumping and recharge intervals of the NoVOCs™ well. Hand measurements of water level rise at the upper recharge interval are also plotted. Drawdown data for the pumping interval show that the water level changed quickly and approached a steady state in a very short time. The drawdown recovery was just as rapid after the pump was turned off. This type of drawdown response makes analysis of transient state data difficult or impossible. In the other hand, water level rise data for the recharge interval show a longer transient stage at the beginning of each test step.

Pressure transducer and hand measurement data collected from the observation wells are presented in Figures G2 through G6 (Appendix G). As shown in Figure G2, well MW-45 shows a small water level rise during each step of the dipole flow test. In wells MW-46 and MW-47, some pressure response can be identified at the beginning of each step, but drawdown or water level rise cannot be positively measured at these two wells. Observation wells MW-48, MW-49, MW-51, MW52, MW53, and MW-54 showed very little or no response to the dipole flow test.

4.7 WATER QUALITY PARAMETERS

Water quality parameters including temperature, specific conductance, pH, reduction/oxidation potential, dissolved oxygen, salinity, and turbidity were measured in water from the pump discharge line during the pumping tests. A summary of the water quality parameter measurements is provided in Table 4-6. In general, results for the water quality parameters are higher in the lower screened zone, with the exception of pH and temperature. This finding is also supported by VOC concentration data from the wells at the demonstration site, which exhibit higher concentrations in samples from the deep wells than in samples from the shallow wells.

Specific conductance and salinity values measured during pumping of the upper screened interval averaged 22.2 micromhos per centimeter (Fmhos/cm) and 2.26 percent, respectively, while the same parameters measured during pumping of the lower screen interval averaged 27.4 Fmhos/cm and 2.71 percent. These results are consistent with the range of values and trend toward increased specific conductance and salinity with depth. Average temperature measured while pumping the upper and lower screened intervals was about 21.7 ?C. Results of pH measurements while pumping the upper screened interval averaged 7.40, which was higher than the average pH value of 7.03 calculated from measurements collected when pumping the lower screened interval. The average reduction/oxidation potential in the upper interval was 22.7 millivolts (mv), while the average reduction/oxidation potential (Eh) in the lower interval was minus 30.5 mv. Dissolved oxygen concentrations also increased from an average of 7.92 milligrams per liter (mg/L) in the upper screened interval to 8.27 mg/L in the lower screened interval. Because the packer seal was not set appropriately during the July 22, 1998, step drawdown test in the upper screened interval, water quality measurements from the test were not used in calculating average water quality values.



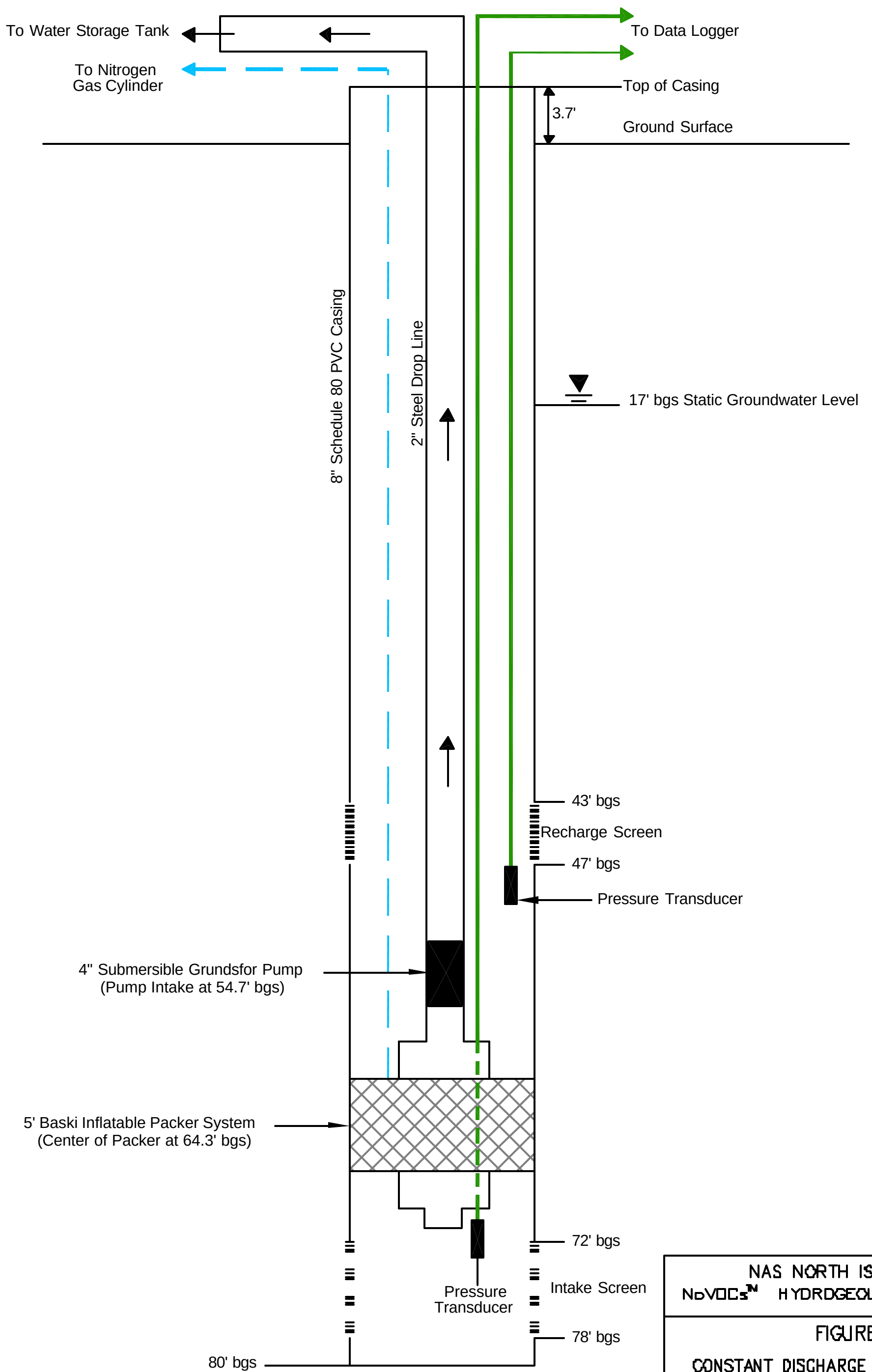
Vertical Scale: 1"=10'

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 4-1

STEP DRAWDOWN TEST-UPPER SCREENED INTERVAL PUMPING WELL CONFIGURATION

Tetra Tech EM Inc.



Vertical Scale: 1"=10'

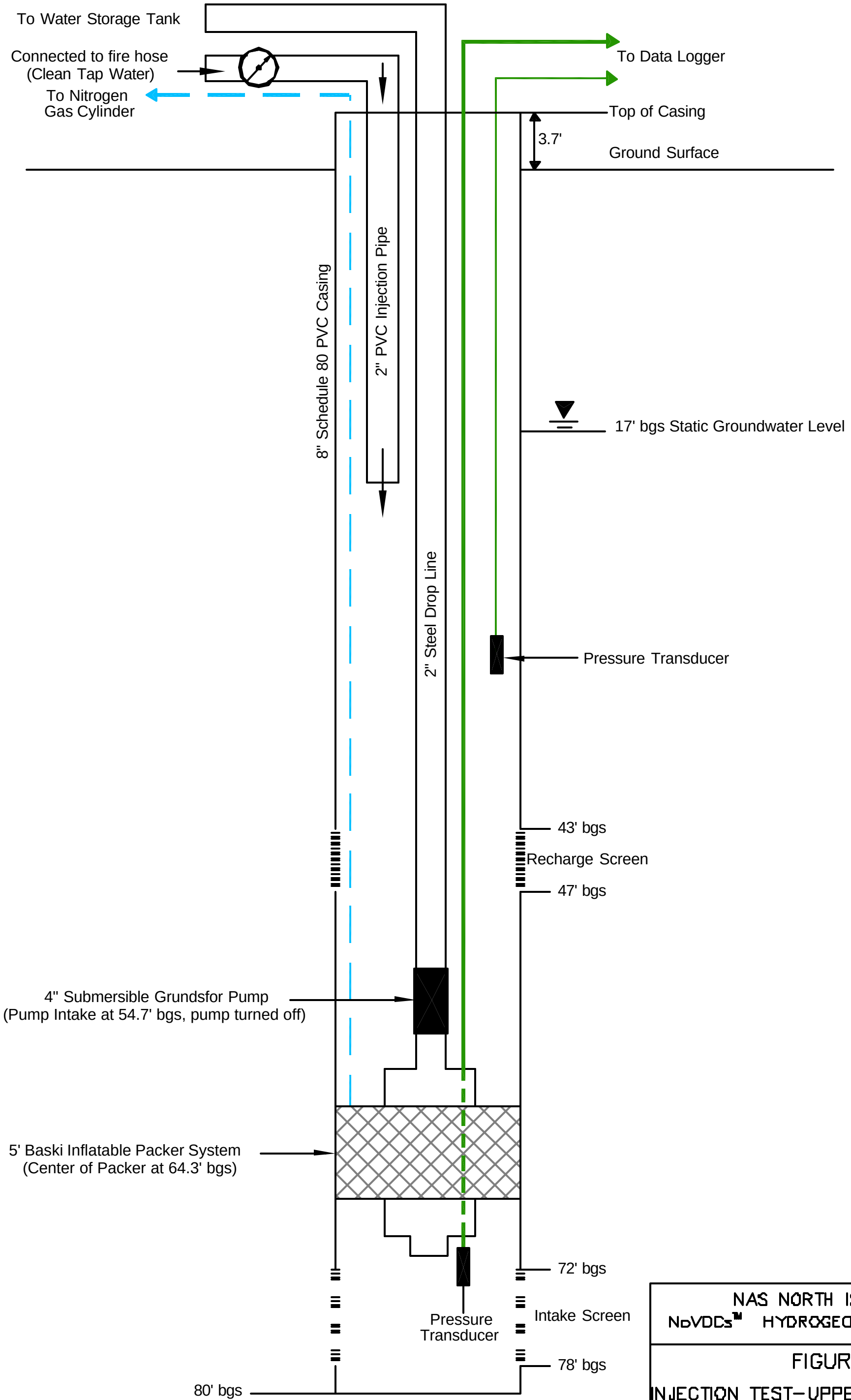
NAS NORTH ISLAND SITE 9

NDVOCs™ HYDRGEOLOGICAL INVESTIGATION

FIGURE 4-2

CONSTANT DISCHARGE PUMPING TEST-UPPER SCREENED INTERVAL PUMPING WELL CONFIGURATION

Tetra Tech EM Inc.



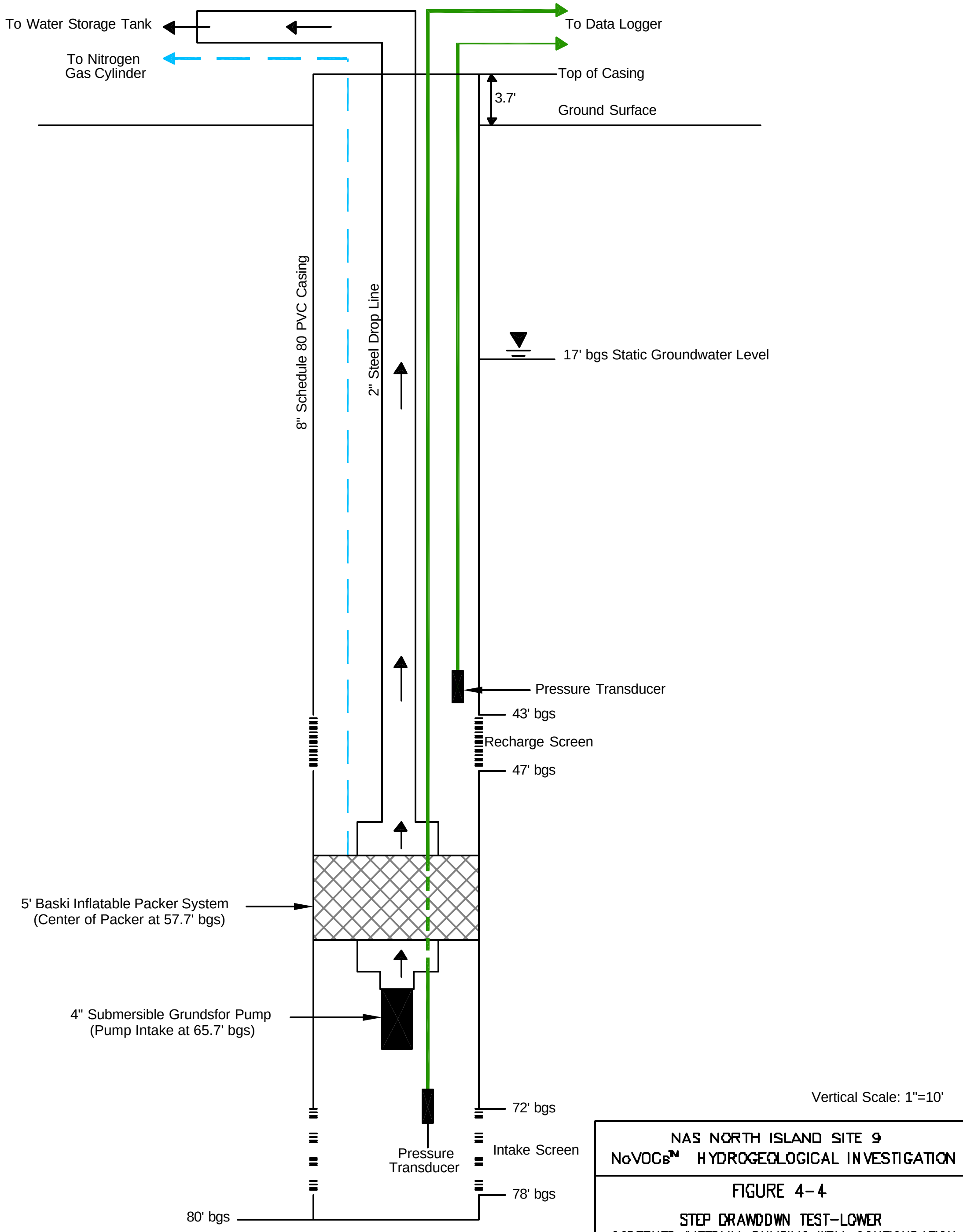
Vertical Scale: 1"=10'

NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 4-3

INJECTION TEST-UPPER SCREENED INTERVAL
INJECTION WELL CONFIGURATION

Tetra Tech EM Inc.

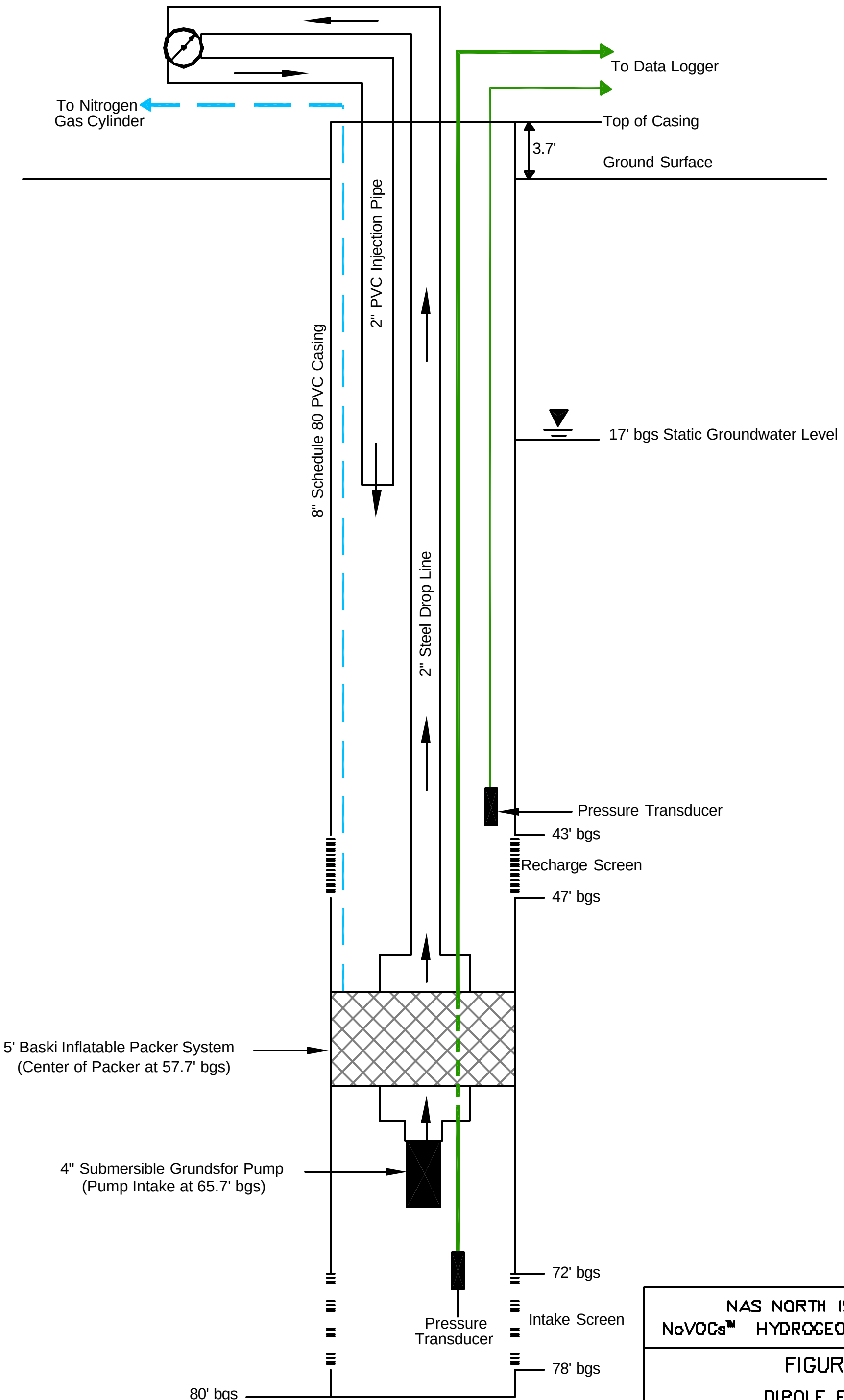


NAS NORTH ISLAND SITE 9
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 4-4

STEP DRAWDOWN TEST-LOWER
SCREENED INTERVAL PUMPING WELL CONFIGURATION

Tetra Tech EM Inc.



Vertical Scale: 1"=10'

NAS NORTH ISLAND SITE 9

NoVOCs™ HYDROGEOLOGICAL INVESTIGATION

FIGURE 4–5

DIPOLE FLOW TEST
WELL CONFIGURATION

Tetra Tech EM Inc.

TABLE 4-1

TEST EXECUTION SUMMARY
STEP DRAWDOWN TEST UPPER SCREEN INTERVAL
JULY 27, 1998
NoVOCs™HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Step	Pumping Rate	Time	Comments
0	NA	14:22	Static groundwater elevation at 17.35 feet below ground surface in the upper screened portion of the NoVOCs™well
1	43 gpm	14:30 to 14:47	Water level reached pump intake, a water level decrease of about 37 feet in the upper screened portion of the NoVOCs™well
Recovery	NA	14:47 to 16:00	Pump shut off; aquifer recovery monitored. Transducer lowered about 5 feet at 15:40.
2	10 gpm	16:00 to 16:11	Water level in well decreased 5.9 feet from initial level in upper screened portion of the NoVOCs™well
Recovery	NA	16:11 to 16:30	Pump shut off (circuit breaker problem); aquifer recovery monitored.
3	15 gpm	16:30 to 17:15	Water level decreased about 11.0 feet from initial level in the upper screened portion of the NoVOCs™well
4	20 gpm	17:15 to 18:00	Water level decreased about 14.2 feet from initial level in the upper screened portion of the NoVOCs™well
Recovery	NA	18:00 to 18:42	Pump shut off; aquifer recovery monitored

Notes:
NA Not applicable
gpm Gallons per minute

TABLE 4-2

TEST EXECUTION SUMMARY
CONSTANT DISCHARGE PUMPING TEST   UPPER SCREEN INTERVAL
JULY 28 THROUGH 30, 1998
NoVOCs™HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Step	Pumping Rate	Time	Comments
0	NA	07:54 (7/28)	Initial groundwater elevation at 17.79 feet below ground surface in the upper screened portion of the NoVOCs™well
1	20 gpm	08:00 (7/28) to 16:00 (7/29)	A total drawdown of 16.4 feet observed in the upper screened portion of the NoVOCs™well
Recovery	NA	16:00 (7/29) to 14:00 (7/30)	Pump shut off; aquifer recovery monitored

Notes:

gpm Gallons per minute
NA Not applicable

TABLE 4-3

TEST EXECUTION SUMMARY
INJECTION TEST   UPPER SCREEN INTERVAL
JULY 31 AND AUGUST 1, 1998
NoVOCs™HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Step	Injection Rate	Time	Comments
0	NA	14:55 (7/31)	Initial groundwater elevation at 17.47 feet below ground surface.
1	5 gpm	15:00 to 16:00	Water level in well increased 3.3 feet from initial level in upper screened portion of the NoVOCs™well
2	15 gpm	16:00 to 17:00	Water level increased about 6.0 feet from Step 1 in the upper screened portion of the NoVOCs™well
3	22 gpm	17:00 to 18:00	Water level increased about 5.1 feet from Step 2 in the upper screened portion of the NoVOCs™well
4	30 gpm	18:00 to 18:04	Water level increased about 3.6 feet from Step 3 (water discharging at ground surface through piezometer)
5	25 gpm	18:04 to 18:18	Water level increased about 2.5 feet from Step 3 in the upper screened portion of the NoVOCs™well
Recovery	NA	18:18 (7/31) to 08:15 (8/1)	Aquifer recovery data collected

Notes:

gpm   Gallons per minute
NA   Not applicable

TABLE 4-4

TEST EXECUTION SUMMARY
STEP DRAWDOWN TEST LOWER SCREEN INTERVAL
AUGUST 1 AND 2, 1998
NoVOCs™HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Step	Pumping Rate	Time	Comments
0	NA	12:19 (8/1)	Initial groundwater elevation at 17.19 feet below ground surface in the upper screened portion of the NoVOCs™well
1a	40 gpm	12:30 to 12:40	Checking integrity of packer seal. Water decreased 11.4 feet from static in lower screened portion of the NoVOCs™well. Packer seal leaking.
Recovery	NA	12:40 to 13:00	Packer deflated and reinflated
1b	50 gpm	13:00 to 14:00	Recheck packer seal integrity. Packer seal integrity OK. Water level in well decreased 15.1 feet from initial level in lower screened portion of the NoVOCs™well
2	64 gpm	14:00 to 15:00	Water level decreased about 20.8 feet from initial level in the lower screened portion of the NoVOCs™well.
Recovery	NA	15:00 to 15:30	Pump shut off; aquifer recovery monitored
3	30 gpm	15:30 to 16:30	Water level decreased about 9.6 feet from initial level in the lower screened portion of the NoVOCs™well
Recovery	NA	16:30 (8/1) to 0730 (8/4)	Pump shut off; aquifer recovery monitored

Notes:
gpm Gallons per minute
NA Not applicable

TABLE 4-5

TEST EXECUTION SUMMARY
DIPOLE FLOW TEST
AUGUST 5 THROUGH 7, 1998
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Step	**Injection Rate**	**Time**	**Comments**
0	NA	11:29 (8/5)	Initial groundwater elevation at 20.69 feet in upper section of the NoVOCs™ well
1	5 to 6 gpm	11:35 to 12:29	Water level increased about 5.3 feet from initial water level in the upper screened section of the NoVOCs™ well. Water level decreased about 2.2 feet from static water level in lower screened section of the NoVOCs™ well.
2	10 gpm	12:29 to 13:40	Water level increased about 3.3 feet from Step 1 water level in the upper screened section of the NoVOCs™ well. Water level decreased about 1.5 feet from Step 1 in the lower screened section of the NoVOCs™ well.
3	15 gpm	13:40 to 14:41	Water level increased about 2.8 feet from Step 2 water level in the upper screened section of the NoVOCs™ well. Water level decreased about 1.0 foot from Step 2 in the lower screened section of the NoVOCs™ well.
4	20 gpm	14:41 to 15:47	Water level increased about 3.8 feet from Step 3 water level in the upper screened section of the NoVOCs™ well. Water level decreased about 1.8 feet from Step 3 in the lower screened section of the NoVOCs™ well.
5	24 to 25 gpm	15:47 to 16:41	Water level increased about 2.3 feet from Step 4 water level in the upper screened section of the NoVOCs™ well. Water level decreased about 1.3 feet from Step 4 in the lower screened section of the NoVOCs™ well.
Recovery	NA	16:41 (8/5) to 09:45 (8/7)	Aquifer recovery data collected

Notes:

gpm Gallons per minute
NA Not applicable

TABLE 4-6

WATER QUALITY PARAMETERS
AQUIFER PUMPING TESTS
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Date	Time	Temperature (°C)	Specific Conductance (μmhos)	pH	Eh (mv)	Dissolved Oxygen (mg/L)	Salinity (percent)	Turbidity (NTU)
Step Drawdown Test - Upper Screen Interval								
7/22/98	13:25	22	29.7	6.87	32	8.46	2.64	1
7/22/98	13:30	21.8	27.8	7.01	-40	8.48	2.67	53
7/22/98	13:35	22.0	27.3	7.08	-20	8.65	2.68	53
7/22/98	13:40	22.0	27.1	7.12	-29	8.63	2.59	53
7/22/98	--	21.5	27.9	7.17	-89	8.88	2.59	53
7/22/98	15:12	22.2	26.9	7.12	-11	8.72	2.67	1
7/22/98	15:24	21.3	26.9	7.09	-13	8.93	2.68	NM
Average		**21.82**	**27.7**	**7.07**	**-24**	**8.68**	**2.65**	**36**
Constant Rate Pump Test - Upper Screen Interval								
7/27/98	20:20	21.7	23.5	7.03	15	7.76	2.48	67
7/27/98	21:32	21.6	24.4	7.35	42	7.40	2.51	63
7/28/98	08:06	21.5	24.7	7.24	84	7.39	2.47	3
7/28/98	08:17	21.6	24.8	7.21	66	NM	NM	NM
7/28/98	10:23	22.5	24.7	7.33	59	8.44	2.44	60
7/28/98	11:20	22.0	24.5	7.37	30	8.64	2.43	55
7/28/98	12:23	22.0	24.6	7.39	31	8.64	2.43	61
7/28/98	14:26	22.1	23.9	7.39	67	8.54	2.38	54
7/28/98	15:30	21.8	23.6	7.42	18	8.64	2.38	3
7/28/98	16:36	22.5	23.3	7.41	41	9.62	2.34	3
7/28/98	17:33	21.8	23.2	7.43	37	8.54	2.31	50
7/28/98	19:57	21.6	22.8	7.44	31	7.58	2.25	3
7/28/98	21:14	21.5	22.5	7.45	-1	7.46	2.25	0
7/28/98	22:18	21.6	22.3	7.46	-9	7.43	2.22	0
7/28/98	23:09	21.4	22.2	7.47	-14	7.39	2.21	2
7/29/98	00:18	21.6	22.0	7.44	-15	7.33	2.19	0
7/29/98	01:15	21.6	21.7	7.43	-13	7.21	2.19	2
7/29/98	02:17	21.6	23.0	7.43	-7	7.30	2.18	4
7/29/98	03:15	21.6	23.2	7.43	-8	7.56	2.14	3
7/29/98	04:24	21.6	22.8	7.41	-7	7.62	2.13	2
7/29/98	05:19	21.6	23.0	7.44	-16	7.51	2.14	1
7/29/98	06:12	21.6	23.1	7.45	-9	7.56	2.16	5
7/29/98	07:00	21.3	18.7	7.47	-4	7.64	2.15	9
7/29/98	10:25	21.7	23.7	7.48	51	7.92	2.11	1
7/29/98	12:30	22.0	23.1	7.50	49	8.27	2.09	3
7/29/98	14:30	27.4	20.0	7.44	45	8.49	2.09	0
7/29/98	15:54	21.8	22.6	7.49	49	8.38	2.04	2
Average		**21.95**	**23.03**	**7.40**	**22.67**	**7.93**	**2.26**	**17.54**

TABLE 4-6

WATER QUALITY PARAMETERS
AQUIFER PUMPING TESTS
NoVOCs™ HYDROGEOLOGICAL INVESTIGATION
NAS NORTH ISLAND

Date	Time	Temperature (°C)	Specific Conductance (μmhos)	pH	Eh (mv)	Dissolved Oxygen (mg/L)	Salinity (percent)	Turbidity (NTU)
Step Drawdown Test - Lower Screen Interval								
8/1/98	13:34	21.8	24.2	6.97	-14	8.46	2.70	53
8/1/98	14:13	21.7	27.0	7.02	-31	8.37	2.70	2
8/1/98	14:30	21.7	27.0	7.11	-32	8.05	2.71	0
8/1/98	14:52	21.7	27.8	7.06	-32	8.35	2.72	62
8/1/98	15:46	21.9	29.0	7.02	-36	8.33	2.71	3
8/1/98	16:16	21.7	29.4	7.01	-38	8.06	2.72	6
Average		**21.8**	**27.4**	**7.03**	**-31**	**8.27**	**2.71**	**21**

Notes:

° C	Degrees Celsius.
μmhos	Micromhos
mv	Millivolts
mg/L	Milligrams per liter
NTU	Nephelometric turbidity units
NM	Not measured
Eh	Reduction/oxidation potential

5.0 DATA INTERPRETATION

This section interprets and discusses the data collected during the aquifer tests and the tidal influence study, including groundwater tidal influence correction for the pumping test data, calculations of well-specific yield and efficiency, calculations of aquifer hydraulic parameters, calculations of the mean groundwater levels, calculations of fresh water equivalent heads (density correction) and estimation of groundwater flow patterns.

5.1 TIDAL INFLUENCE CORRECTION

Groundwater levels in the vicinity of the NoVOCs™ well are affected by tidal fluctuations in San Diego Bay because of hydraulic communication between the groundwater and the bay and the proximity of the site to the bay. Water level data derived from pumping tests must be corrected for tidal influence before they can be used to estimate aquifer parameters, except when the water level fluctuation caused by tides is insignificant in comparison with drawdown (such as in the pumping well). This section discusses the principles of and approaches to the tidal influence correction, and applies the corrections to the pumping test water level data.

5.1.1 Relationship Between Tide and Groundwater Fluctuation

Observed groundwater level fluctuations can be divided into two components: (1) tidally induced fluctuations, and (2) fluctuations caused by other factors. This relationship can be described by the following equation:

$$\frac{dh'(t)}{dt} = \frac{dh(t)}{dt} - E_{tide}\frac{dH(t-t_{lag})}{dt} \tag{5-1}$$

where

h'	=	Groundwater elevations without tidal influence [L]
h	=	Observed groundwater elevation [L]
H	=	Tidal elevation in surface water body [L]
E_{tide}	=	Tidal efficiency [dimensionless]

t	=	The time when groundwater elevation was measured [T]
t_{lag}	=	Time lag between tidal effects in surface water body and corresponding effects at groundwater observation points [T]

The first term of the right-hand side of Equation 5-1 represents the observed groundwater level fluctuation, and the second term of the right-hand side represents tidally induced groundwater level fluctuation. The left-hand side of the equation represents groundwater fluctuations caused by other factors, such as pumping of groundwater, lateral changes in recharge or discharge in the aquifer, and other daily and seasonal water level changes (such as those caused by barometric pressure changes).

As shown in Equation 5-1, the relationship between the tidal fluctuation in the surface water levels and the tidally induced groundwater level fluctuation is determined by two parameters: tidal efficiency (E_{tide}), and time lag (t_{lag}). The tidal efficiency is defined as the ratio of tidally induced changes in groundwater levels to the tidal changes in the surface water body. The time lag represents the time difference between the tidal changes in the surface water body and corresponding changes in groundwater levels. Both the tidal efficiency and time lag are determined by a number of factors, including aquifer hydraulic conductivity and storativity (or diffusivity), aquifer thickness, and distance from the observation well to the surface water body. The relationship between the tidal influence parameters and the above factors in a homogeneous and isotropic aquifer can be expressed as follows (Jacob 1950; Ferris 1951):

$$E_{tide} = e^{\left(-x\sqrt{\frac{p\,S}{t_p KB}}\right)} \tag{5-2}$$

and

$$t_{lag} = x\sqrt{\frac{t_p\,S}{4pKB}} \tag{5-3}$$

where

x	=	Distance from the observation well to the coast line [L]
S	=	Aquifer storativity [dimensionless]
K	=	Aquifer hydraulic conductivity [LT^{-1}]
B	=	Aquifer thickness (L)
t_p	=	Tidal period (time between consecutive high and low tides) [T]

Based on Equations 5-2 and 5-3, the tidal efficiency will increase as aquifer hydraulic conductivity and aquifer thickness increase, and decrease as aquifer storativity and the distance from the coast increase. The tidal time lag will decrease as aquifer hydraulic conductivity and aquifer thickness increase, and increase as aquifer storativity and the distance from the coast increase. Based on these relationships, the time lag will generally decrease when tidal efficiency increases. Theoretically, the tidal efficiency and time lag are not functions of time.

Equations 5-2 and 5-3 are based on the following assumptions:

- Tidal fluctuations can be described as a sinusoidal function
- One-dimensional groundwater flow is perpendicular to the shoreline
- The aquifer is homogeneous and isotropic
- The aquifer is under confined conditions
- The shoreline is considered a lateral boundary that is perpendicular to groundwater flow direction
- The observation well fully penetrates the aquifer

In reality, aquifer conditions rarely meet all the above assumptions (Erskine 1991; Serfes 1991). Consequently, tidal efficiency and time lag are generally not calculated from Equations 5-2 and 5-3; the equations have been presented to provide a theoretical definition of tidal efficiency and time lag. Instead, these two parameters are usually determined directly from observed groundwater and surface water level fluctuations. A procedure to calculate tidal efficiency and time lag from the observed groundwater and tidal data is presented in the following section.

5.1.2 Procedure for Calculating Tidal Efficiency and Time Lag

In order to calculate the tidal efficiency and time lag from the observed surface water (San Diego Bay) and groundwater level data, an observation period should be selected during which the groundwater level fluctuations are primarily affected by tide; other factors affecting groundwater levels (such as rainfall infiltration and pumping) should be negligible. From Equation 5-1, if the effects of factors other than tidal fluctuations can be ignored ($dh' / dt = 0$), the observed groundwater fluctuations can be used directly to represent the tidally induced fluctuations, as expressed by the following equation:

$$\frac{dh(t)}{dt} = E_{tide} \frac{dH(t - t_{lag})}{dt} \tag{5-4}$$

For a time period from t_0 to t_1 in the groundwater observation record, the solution of Equation 5-4 can be obtained by integration as follows:

$$\int_{t_0}^{t_1} \frac{dh(t)}{dt} dt = \int_{t_0}^{t_1} E_{tide} \frac{dH(t - t_{lag})}{dt} dt \tag{5-5}$$

This integral can be expressed as follows:

$$h(t_1) - h(t_0) = E_{tide} \left[H(t_1 - t_{lag}) - H(t_0 - t_{lag}) \right] \tag{5-6}$$

Based on Equation 5-6, the tidal efficiency can be calculated as follows:

$$E_{tide} = \frac{h(t_1) - h(t_0)}{H(t_1 - t_{lag}) - H(t_0 - t_{lag})} \tag{5-7}$$

Equation 5-7 represents the tidal efficiency for the period from t_0 to t_1.

In principle, tidal efficiency and time lag are constants that do not vary with time. However, these parameters may vary from time to time because of groundwater flow conditions and inconsistencies in the amplitude and periodicity of tidal fluctuations. In general, various tidal efficiencies can be calculated using Equation 5-7 for different periods of the data. Different time lags can also be determined independently using different data sets. A procedure for calculation of tidal efficiency and time lag is described as follows:

(1) Choose a period in the observed groundwater level record when groundwater fluctuations are almost exclusively caused by the tidal fluctuations.

(2) Identify the high tide and low tide in tidal records, and identify corresponding groundwater high level and low level in groundwater level records.

(3) Calculate tidal time lag as follows:

$$t_{lag} = t_{i(tide)} - t_{i(gw)} \tag{5-8}$$

where

$t_{i(tide)}$	=	Time for the i^{th} high (or low) tide [T]
$t_{i(gw)}$	=	Elevation time for the i^{th} high (or low) groundwater elevation corresponding to the i^{th} high (or low) tide [T]

(4) Calculate the tidal efficiency using the following equation:

$$E_{tide} = \frac{h_i - h_{i-1}}{H_i - H_{i-1}} \tag{5-9}$$

where

H_i	=	The i^{th} high (or low) tidal elevation (L)
h_i	=	The i^{th} high (or low) groundwater elevation corresponding to the i^{th} high (or low) tide [T]

Figure 5-1 presents a graphical illustration of the time lag and tidal efficiency (amplitudes of the tidal fluctuations in San Diego Bay and MW-45) based on a comparison of San Diego Bay water levels and groundwater levels in observation well MW-45.

5.1.3 Calculation of Tidal Efficiency and Time Lag Using April 1998 Tidal Study Data

Tidal efficiency and time lags were calculated based on the groundwater elevation data collected at eight observation wells during the April 1998 tidal influence study. The groundwater elevations in the wells were recorded at 10-minute intervals for 10 days. During this period, the surface water level data in San Diego Bay can be divided into 39 monotonic segments (that is, water levels from high to low or low to high tide). Groundwater levels at all observation wells clearly showed tidally influenced fluctuations that correspond to the tidal fluctuations in San Diego Bay. The average amplitude of tides in the bay for the 10-day period was 5.27 feet, and the average amplitude of groundwater fluctuations in various observation wells ranged from 0.36 to 0.46 feet. The maximum, minimum, and mean tidal amplitude and groundwater fluctuations are presented in Table 5-1.

The tidal efficiency and time lags were calculated for each of the 39 monotonic tidal segments during the 10-day tidal study using the procedure described in section 5.1.2. Table 5-1 shows the maximum, minimum, and mean estimated tidal efficiencies and time lags for the eight observation wells at the site.

As shown in the table, both the tidal efficiency and time lag vary slightly at the various observation well locations, but vary significantly during different tidal cycles, as indicated by the significant difference between minimum and maximum values of tidal efficiency and time lag. The mean tidal efficiency (average tidal efficiency for all 39 tidal periods) at the eight observation wells ranges from 0.07 to 0.09. The higher tidal efficiency values were measured at downgradient observation wells (MW-52 and MW-53), which are the closest to the bay of the wells monitored. The difference between the maximum and minimum tidal efficiency during different tidal cycles was about 0.03 for most of the wells.

The mean time lags (average time lag for all 39 monotonic tidal periods) did not change significantly from well to well, ranging from 69 minutes to 72 minutes. However, the time lags in each well changed considerably during different tidal cycles (Table 5-1).

5.1.4 Procedures for Tidal Correction of Groundwater Drawdown Data

When an aquifer hydraulic test is conducted in a tidally influenced aquifer, groundwater levels are affected by at least two major factors: drawdown from pumping and fluctuation caused by tide. Tidal fluctuation, if significant compared with pumping drawdown, can complicate interpretation of test data. Literature review shows that correction of non-steady state pumping test data for tidal influence has not been much studied and that no readily applicable methods are currently available. Therefore, in this section, two different approaches are developed and discussed. The two approaches? that is, the tidal correction of the drawdown data collected during the upper aquifer zone constant discharge pumping test? are presented in this section.

5.1.4.1 Approach Based on the Linear Relationship Between Groundwater and Tide

As shown in Equation 5-1, observed groundwater level fluctuations in tidally influenced aquifers are the sum of tidally induced fluctuations and water level changes caused by other factors. For the time period from t_0 to t, differential Equation 5-1 can be solved by integration, as follows:

$$\int_{t_0}^{t} \frac{dh'}{dt}dt = \int_{t_0}^{t} \frac{dh}{dt}dt - \int_{t_0}^{t} E_{tide} \frac{dH(t - t_{lag})}{dt}dt \qquad (5\text{-}10)$$

This integral can be expressed as follows:

$$h'(t) = h(t) - h(t_0) - E_{tide}\left[H(t - t_{lag}) - H(t_0 - t_{lag})\right] + h'(t_0) \tag{5-11}$$

where

$h'(t)$	=	Tidally corrected groundwater elevation at time t [L]
$h'(t_0)$	=	Tidally corrected groundwater elevation at initial time t_0 [L]
$h(t)$	=	Observed groundwater elevation at time t [L]
$h(t_0)$	=	Observed groundwater elevation at initial time t_0 [L]
$H(t- t_{lag})$	=	Tidal elevation at time $t- t_{lag}$ [L]
$H(t_0- t_{lag})$	=	Tidal elevation at time $t_0- t_{lag}$ [L]
E_{tide}	=	Tidal efficiency [dimensionless]
t_{lag}	=	Time lag [T]

This equation shows that the groundwater elevations corrected for tidal influence can be calculated from the observed groundwater elevations, observed tidal elevations, and tidal influence parameters (tidal efficiency and time lag). The equation also shows that the tidal influence component of changes in groundwater level can be expressed as a linear function of tidal fluctuations in surface water.

Water level drawdowns at time t can be defined as:

$$s(t) = h_{ref} - h(t) \tag{5-12}$$

and

$$s'(t) = h_{ref} - h'(t) \tag{5-13}$$

where

h_{ref}	=	Reference groundwater level (a constant) [L]
$s(t)$	=	Observed water level drawdown at time t [L]
$s'(t)$	=	Tidally corrected water level drawdown at time t [L]

Using Equations 5-12 and 5-13 to substitute for h(t), $h(t_0)$, h'(t), and $h'(t_0)$ in Equation 5-11, the tidally corrected water level drawdown can be described as follows:

$$s'(t) = s(t) - s(t_0) - E_{tide}\left[H(t_0 - t_{lag}) - H(t - t_{lag})\right] + s'(t_0) \qquad (5\text{-}14)$$

where

$s(t_0)$	=	Observed water level drawdown at initial time t_0 [L]
$s'(t_0)$	=	Tidally corrected water level drawdown at time t_0 [L]

Both Equations 5-11 and 5-14 assume that the tidal efficiency and time lag are constant over the calculation period from t_0 to t. However, as discussed in the previous section, tidal efficiency and time lag are generally not constant for different tidal periods (tidal cycles). In fact, tidal study data collected in April 1998 at the site demonstrate that tidal efficiency and time lag vary significantly over the 10-day period.

Equations 5-11 and 5-14 are the basis of the first approach (linear relationship) used for tidal correction of the groundwater drawdown data. The tide data were obtained from the San Diego Bay station of the National Oceanic and Atmospheric Administration (NOAA). The linear relationship approach for correcting groundwater drawdown data for tidal influence is described as follows:

(1) Identify the high and low points in the bay tide elevation record, and divide the bay tide record into monotonic segments bounded by consecutive high and low tide elevations.

(2) Identify the high and low groundwater levels in the groundwater drawdown data, and divide the groundwater drawdown data into segments that correspond to the monotonic tidal segments identified in step 1.

(3) Compare each of the bay tidal segments with corresponding groundwater drawdown data segments to determine whether the time spans are similar for the two segments. If the time span for a monotonic tidal segment is different from the corresponding drawdown segment, the time scale of the tidal segment is compressed or expanded by linear interpolation to match the drawdown segment.

(4) The first and last groundwater drawdown segments may or may not match a complete monotonic segment of the bay tide, depending on timing of the pumping test in relation to the tide cycles. Therefore, multiple smaller data segments are used to better match the time scale of the early pumping test data.

(5) Shift the time axis of the bay tidal segments based on the range of the time lag values calculated from the April 1998 tidal study data (Table 5-1). Apply the tidal efficiency

(also Table 5-1) to correct each segment of observed groundwater drawdown using the equation:

$$s'(t) = s(t) - s(0) - E\left[H(0)_0 - H(t)\right] + s'(0) \qquad (5\text{-}15)$$

where

$s'(\tau)$	=	Corrected groundwater drawdown for the segment [L]
$s'(0)$	=	Corrected groundwater drawdown at the start of the segment [L]
$s(\tau)$	=	Observed groundwater drawdown for the segment [L]
$s(0)$	=	Observed groundwater drawdown at the start of the segment [L]
$H(\tau)$	=	Tidal elevation for the segment [L]
$H(0)$	=	Tidal elevation at the start of the segment [L]
E	=	Tidal efficiency for the segment [dimensionless]
τ	=	Time since beginning of the segment [T]

(6) The tidal correction procedure is repeated for all segments of the tidal and groundwater drawdown record.

5.1.4.2 Approach Based on the Best-Fit Equation of Groundwater Tidal Fluctuation

In the second approach for tidal correction of groundwater drawdown data, a tidal influence curve (best-fit equation) is generated for the period of the pumping test that reflects only tidal fluctuations. These tidal influence curves are generated for data from each of the observation wells. Using this approach, fluctuations in groundwater levels calculated from the tidal influence curve are subtracted from the observed drawdown data collected during the pumping test. The corrected drawdown can then be used to calculate aquifer parameters.

The tidal influence curves for observation wells within the radius of influence during a pumping test can be derived from the tidal influence curves for data from wells outside the radius of influence or from tidal curves for the bay tide. Tidal data collected at the observation wells before or after the pumping test cannot be used because the bay tide changes significantly with time. During the pumping test, tidal fluctuation at different wells within the pumping aquifer is generally a function of aquifer hydraulic properties and distance from the shoreline but not a function of time, as described in Equations 5-2 and 5-3.